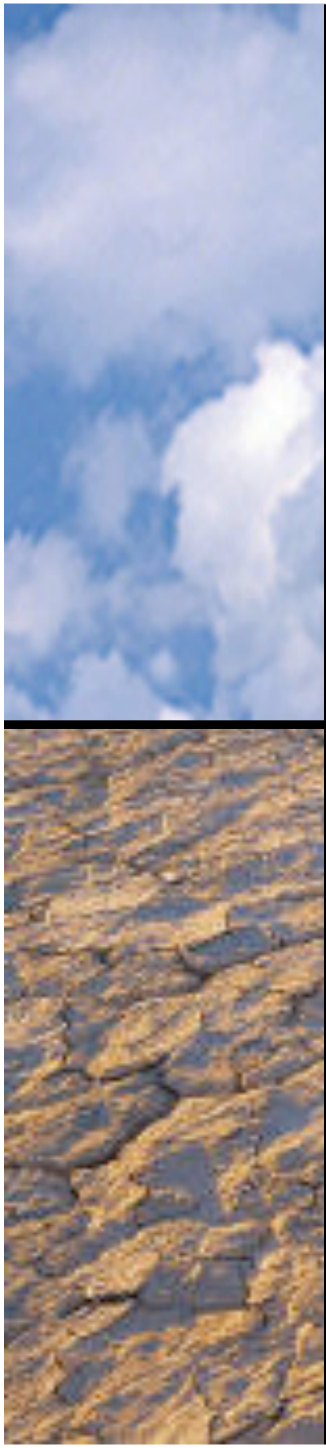

Estimation of Convective Planetary Boundary Layer Evolution and Land-Atmosphere Interactions from MODIS and AIRS

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&
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AIRS Science Team Meeting
27 March 2007

1 BOSTON UNIVERSITY

Motivation

- ***Land-atmosphere interactions and coupling*** **remain weak links in current land surface and atmospheric prediction models**

- **The degree to which the land impacts the atmosphere is difficult to observe, quantify, and simulate given the disparate resolutions and complexity of the *governing processes and feedbacks***

- **The Convective PBL (CBL) serves as a short-term memory of L-A interactions through the diurnal integration of surface fluxes and subsequent evolution of CBL fluxes and states**

- ***Satellite remote sensing*** **offers the ability to monitor temperature and moisture profiles at increasingly high spatial and temporal resolutions**

Can MODIS and AIRS sensors be used to diagnose CBL evolution and provide information on L-A coupling?

Outline

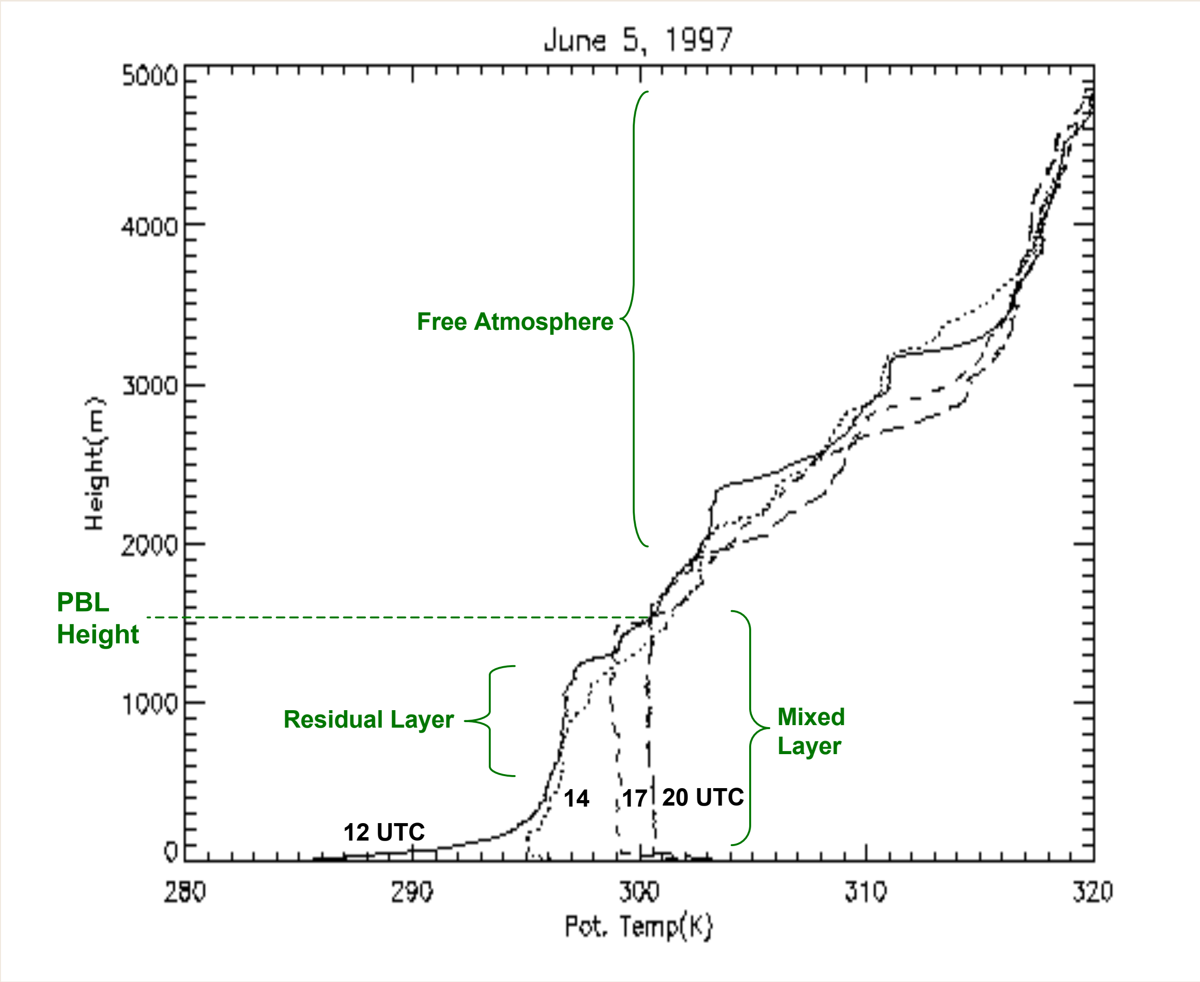
The Role of the CBL in L-A Interactions

L-A Coupling Diagnostics

Remote Sensing of CBL Properties

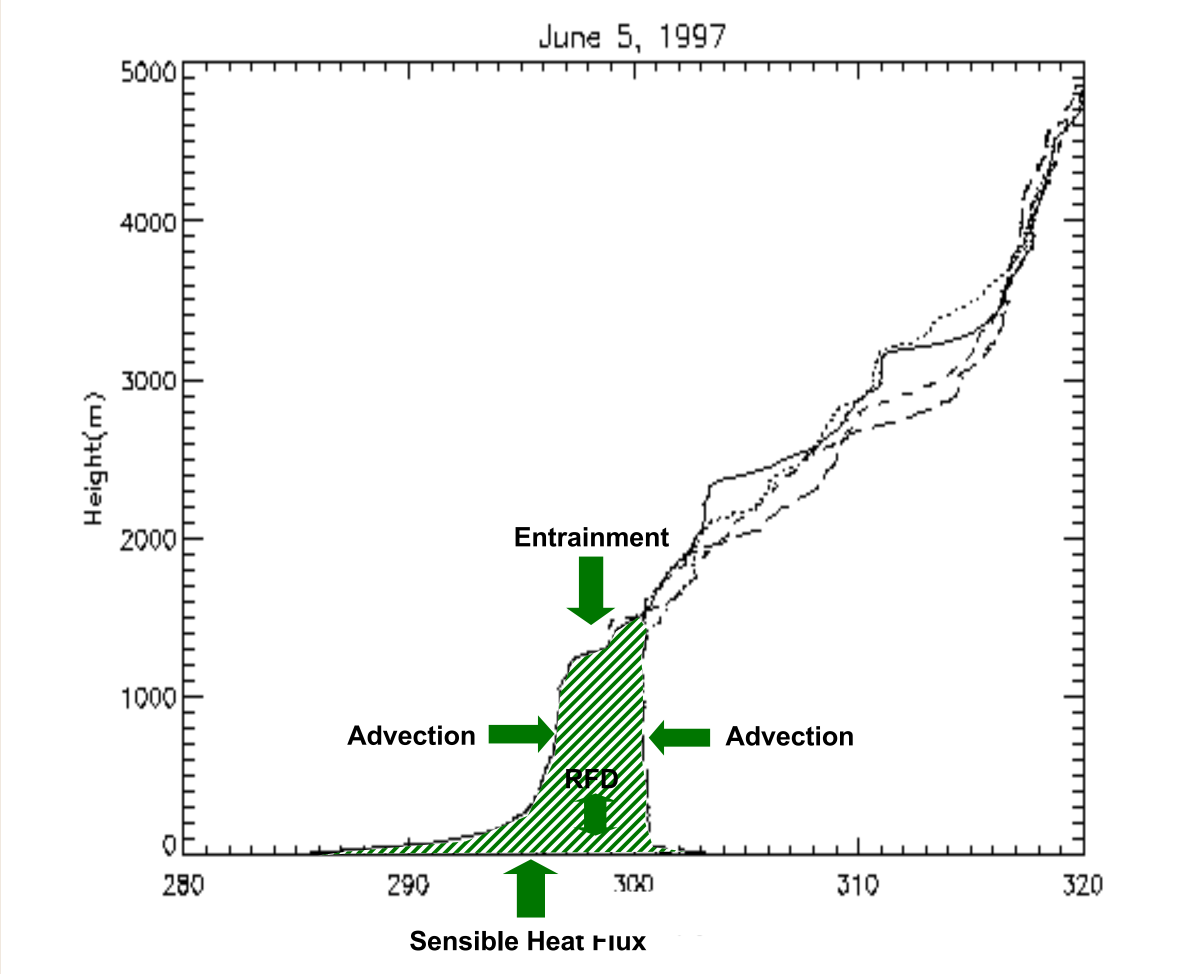
Incorporating CBL Observations into LoCo Studies

CBL Structure and Evolution



Daytime profiles of potential temperature (θ) at the ARM-SGP central facility

CBL Heat Conservation



CBL heat budget determined by L-A processes and feedbacks that are difficult to measure

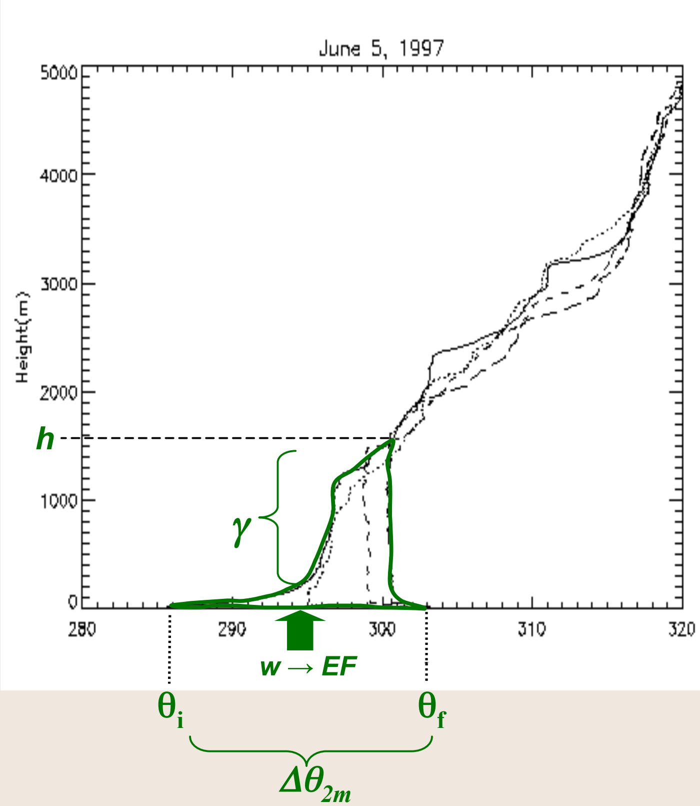
Observable CBL Diagnostics

- **Maximum CBL Height** (***h***)
  - responds directly to the flux of heat into the CBL

- **Atmospheric Stability** (γ)
  - ***dθ/dz*** from 12Z profile
  - Incorporates influence of residual mixed layer

- **Soil Water Content** (***w***)
  - controls partitioning of surface fluxes
  - ~ Evaporative Fraction **(EF)**

- **Change in 2-meter Potential Temperature** ($\Delta\theta_{2m}$)
  - Calculated from 12-20Z
  - sensitive to heat input and CBL height



Outline

The Role of the CBL in L-A Interactions

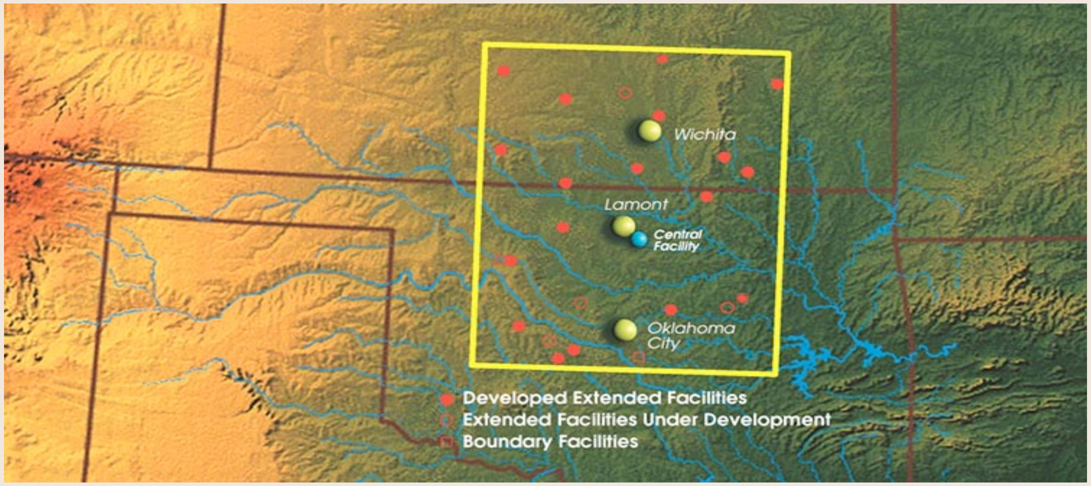
L-A Coupling Diagnostics

- Observed (ARM-SGP)
- Modeled (OSU-1D PBL)
- Feedbacks

Remote Sensing of CBL Properties

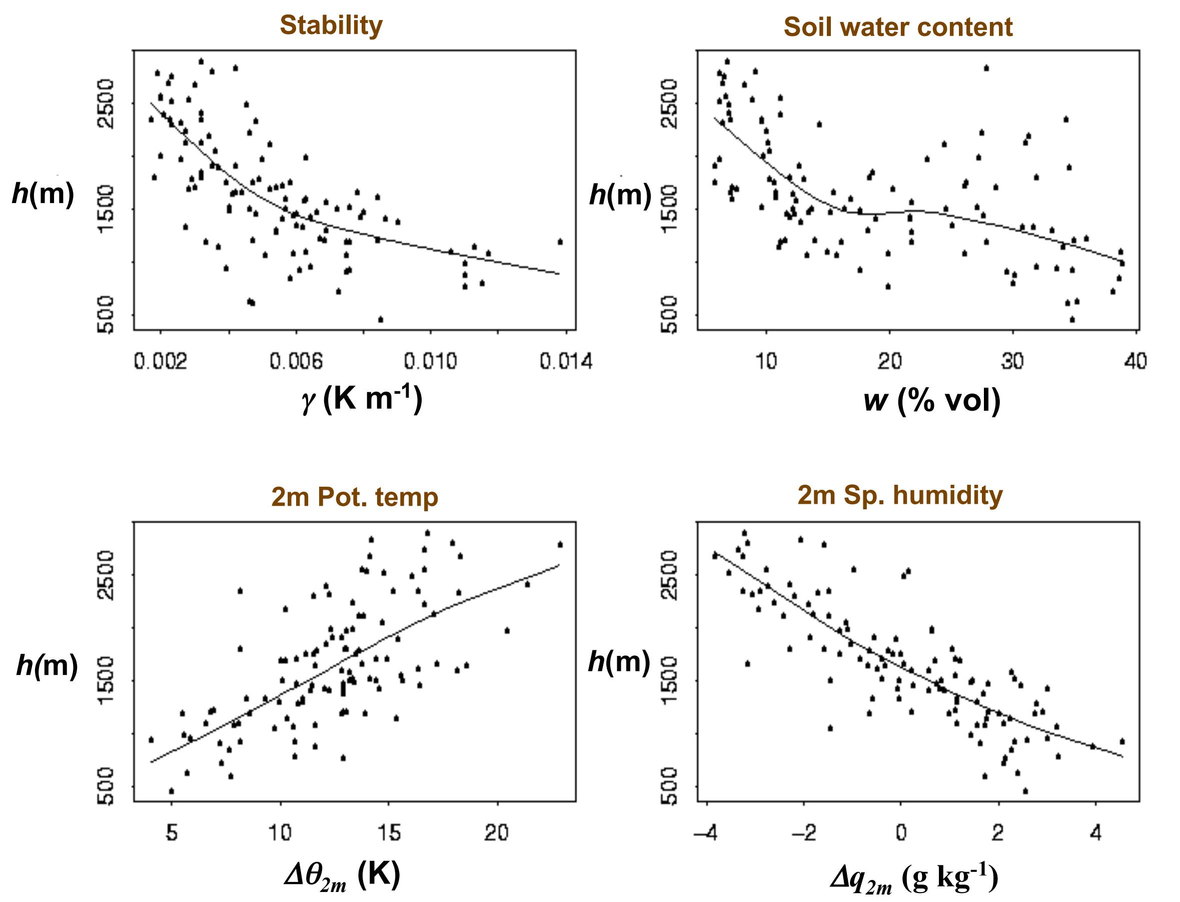
Incorporating CBL Observations into LoCo Studies

ARM-SGP Central Facility (Lamont, OK)



- **Atmospheric data**
  - Radiosondes: 6:30am, 9:30am, 12:30pm, 3:30pm
  - Profiles of temperature, humidity, pressure, and wind
- **Land Surface data**
  - Bowen ratio flux towers
  - Surface meteorological data
  - 5 soil moisture probes (0-5 cm)
  - ▪ Average of 3 surrounding sites + Lamont (~100 km)
- **132 days from JJA of 1997, 1999, and 2001**

Observed CBL Diagnostics

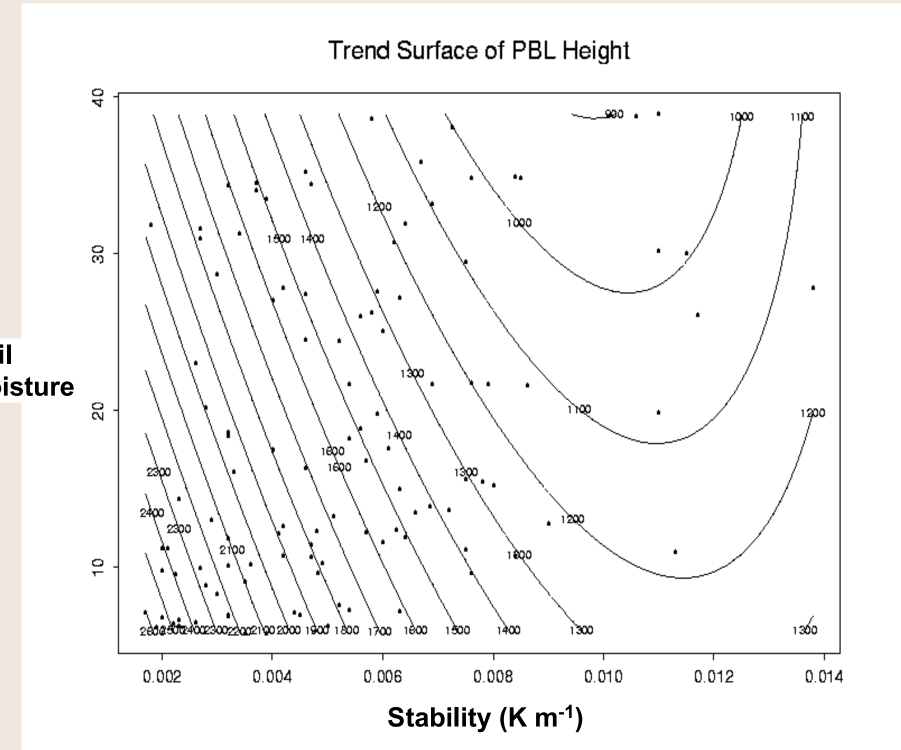


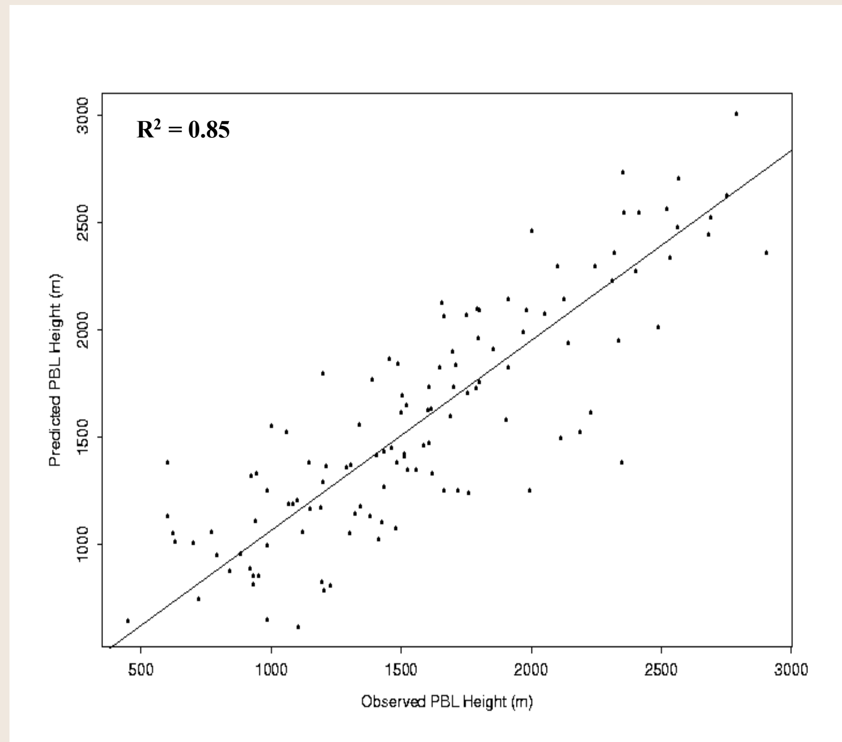
Strong relationships between CBL and land surface properties can be exploited….

Observed CBL Diagnostics

using polynomial models that can predict CBL height….

Soil Moisture





as a function of soil moisture and atmospheric stability

Santanello, J. A., M. A. Friedl, and W. P. Kustas 2005: An Empirical Investigation of Convective Planetary Boundary Layer Evolution and Its Relationship with the Land Surface. *J. Applied Meteorol. 44, 917-932.*

Observed and Modeled CBL Diagnostics

- **L-A coupling is sensitive to *vegetation cover* and *soil type* and complicated by *feedbacks* between the PBL and land surface**
  - L-A relationships are supported by data and extended by simulations
  - Single Column Models
  - Impact offline LSMs

- **Determination of *CBL structure* (CBL Ht., Stability, Residual Layer) offers information on L-A coupling**

Can MODIS and AIRS sensors be used to diagnose CBL evolution and provide information on L-A coupling?

Santanello, J. A., M. A. Friedl, and M. B. Ek, 2007: Convective Planetary Boundary Layer Interactions with the Land Surface at Diurnal Time Scales: Diagnostics and Feedbacks. *J. Hydrometeorol.*, under review.

Outline

The Role of the CBL in L-A Interactions

L-A Coupling Diagnostics

Remote Sensing of CBL Properties

- MODIS/AIRS temperature profiles
- AIRS radiances

Incorporating CBL Observations into LoCo Studies

Temperature Profile Retrievals in the CBL

- **Remote Sensing** now offers the ability to monitor conditions in the lower troposphere on diurnal timescales with unprecedented spatial and spectral resolution.

- **MODIS**
  - Aboard Terra and Aqua
  - 7 vertical levels below 600mb (36 bands)
  - 5 km horizontal resolution
  - 10:30am, 1:30pm local overpasses
  - High horizontal resolution but weak weighting functions in the PBL

- **AIRS(v3)**
  - Aboard Aqua
  - 8 levels below 600mb from (2085 channels)
  - ~50 km horizontal resolution
  - 1:30am/pm local overpasses
  - True ‘sounder’ of the troposphere

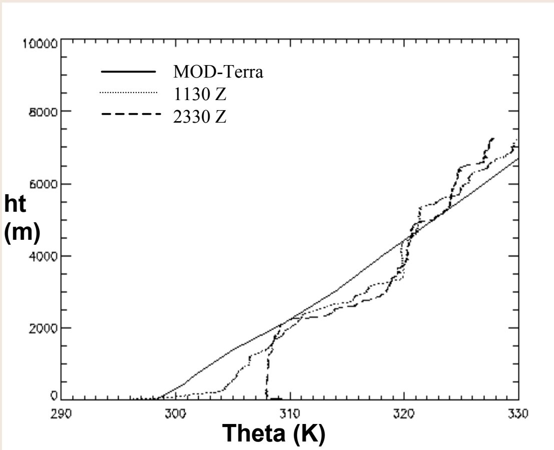
Evaluation

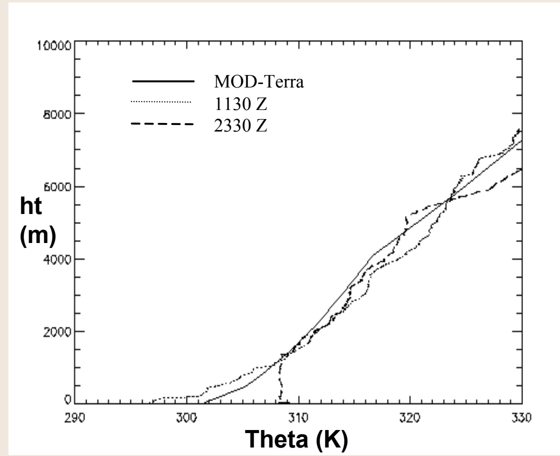
- **44** clear days at ARM-SGP in JJA 2003
- Temperature profile retrievals (L2) and cloud-cleared (L1B) radiances
- 2 complete soil dry-downs
- Daily CBL ranges from 300 - 3650m.

MODIS Profile Evaluation

Profiles of potential temperature retrieved from MODIS-Terra and MODIS-Aqua compared with co-located radiosonde measurements at the ARM-SGP Central Facility

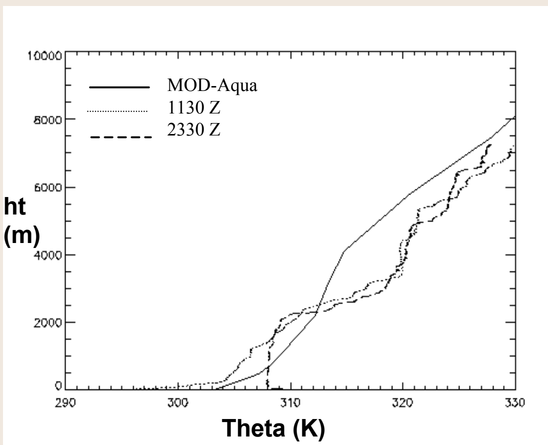
5 July 2003
1755 UTC
(12:55pm)

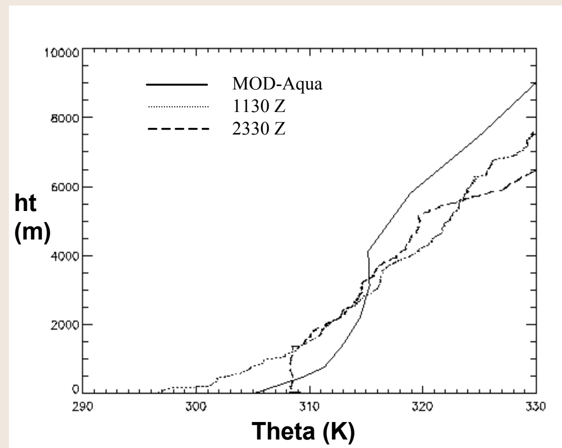




10 July 2003
1635 UTC
(11:35am)

5 July 2003
1930 UTC
(1:30pm)





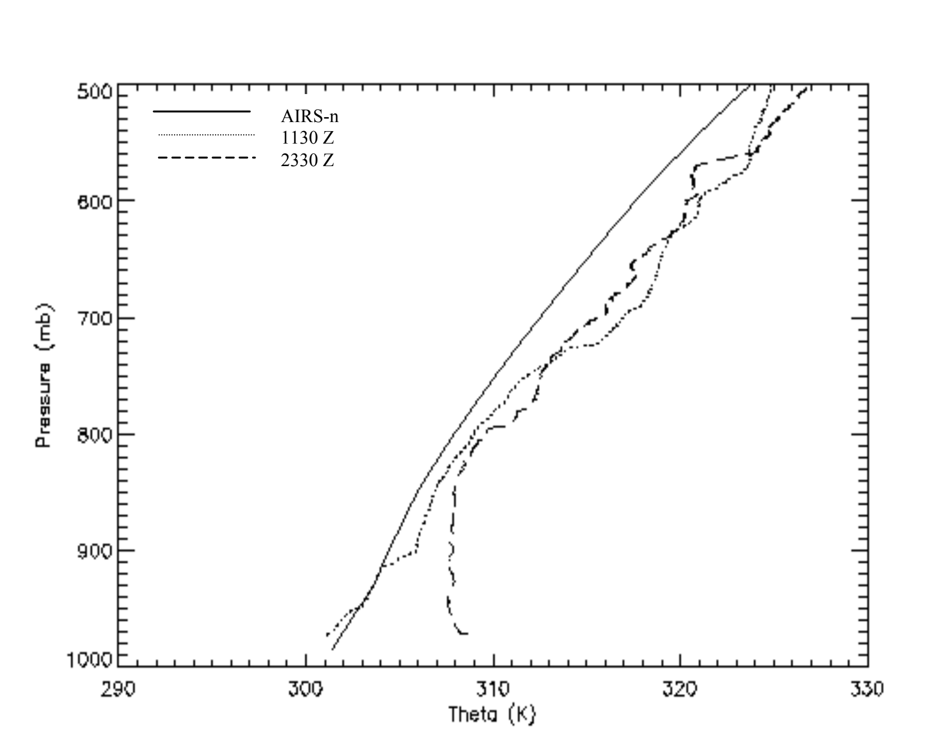
10 July 2003
1945 UTC
(1:45pm)

- **MODIS captures the free atmosphere and 'mean' lapse rate of temperature well**
- **MODIS-Aqua responds to the heating of the mixed-layer, but PBL structure lacking**

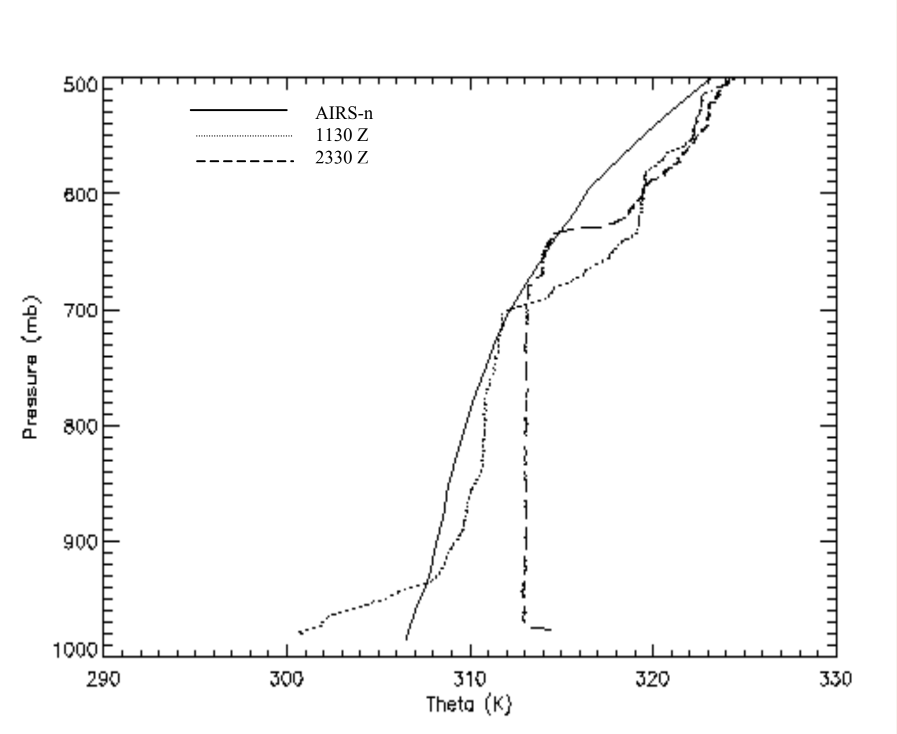
AIRS-Night Evaluation

Profiles of potential temperature retrieved from AIRS-Night

compared with co-located radiosonde measurements at the ARM-SGP Central Facility



4 June 2003 0840 UTC (4:40am)



27 July 2003 0745 UTC (3:45am)

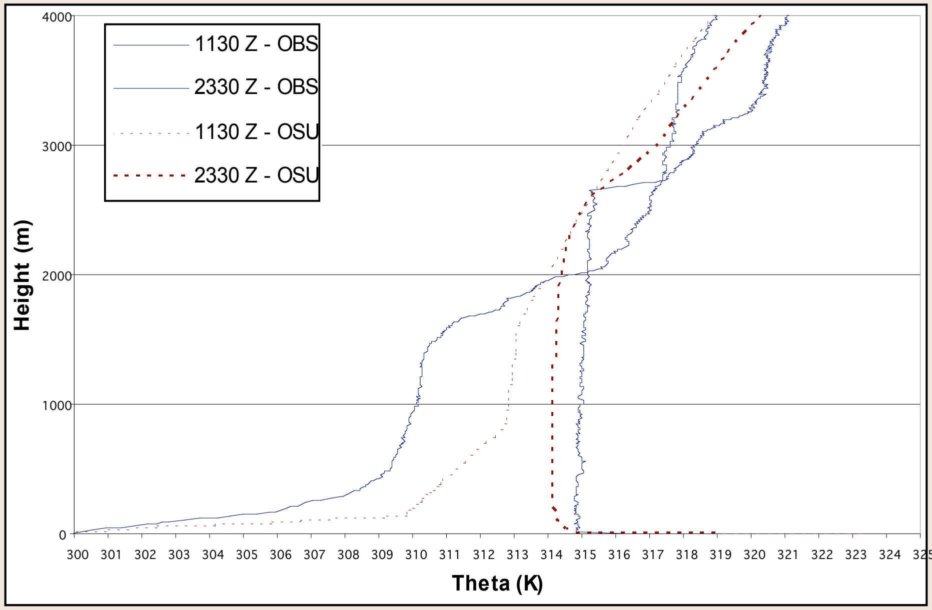
- **Initial (morning) lapse rate is captured well by AIRS-night**
- **Responds to stability in the mixed-layer (and presence of a residual layer)**

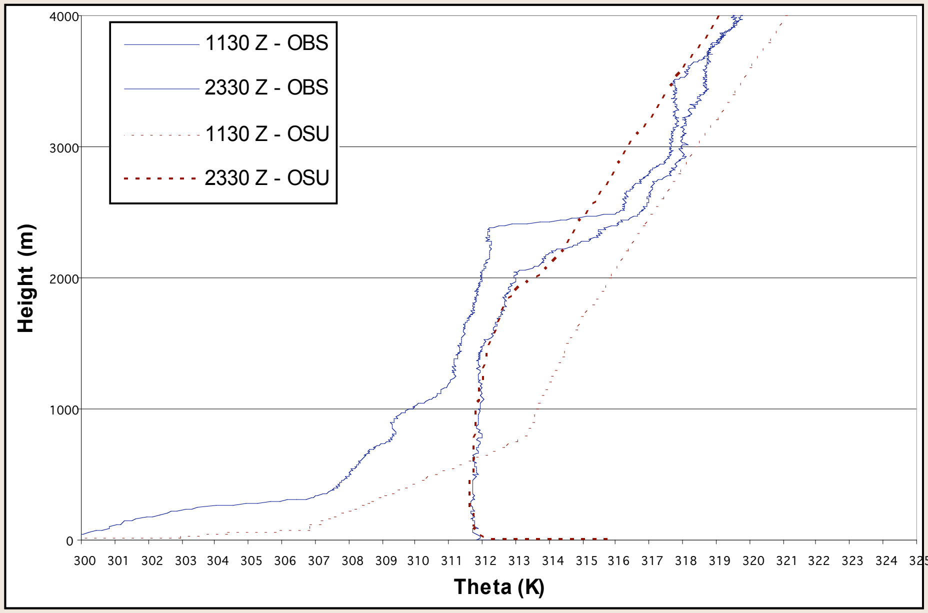
Towards Assimilation of PBL Data

Use retrieved profiles to initialize a SCM or regional coupled model (WRF)

Preliminary Results:

- Use AIRS-Night profiles to initialize the OSU 1-D model



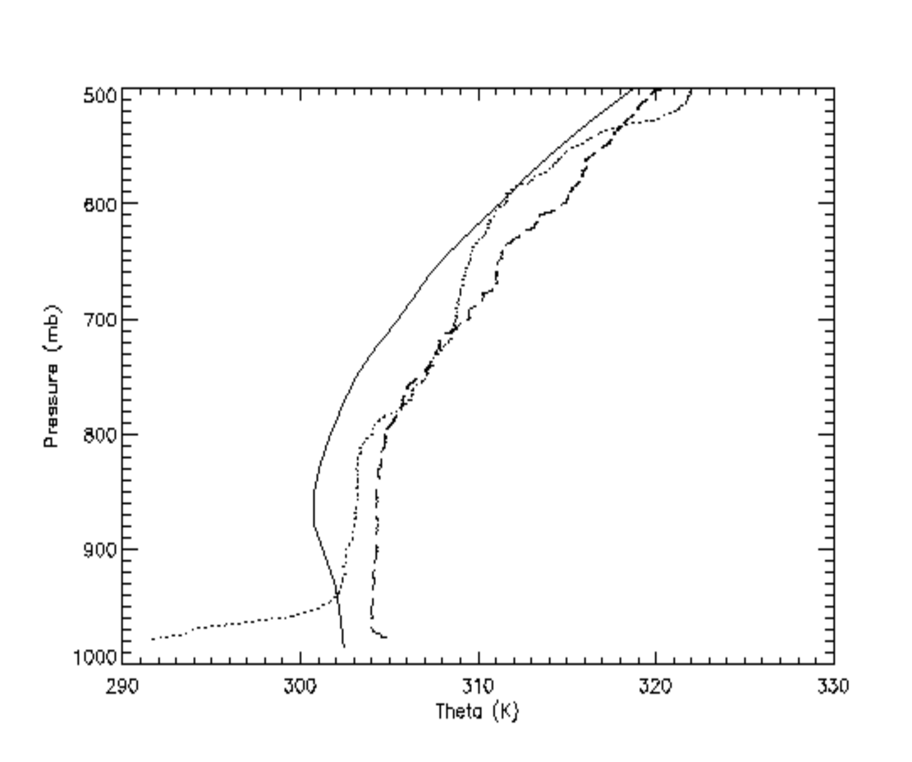


OSU simulations of potential temperature initialized using AIRS data compared with radiosonde measurements

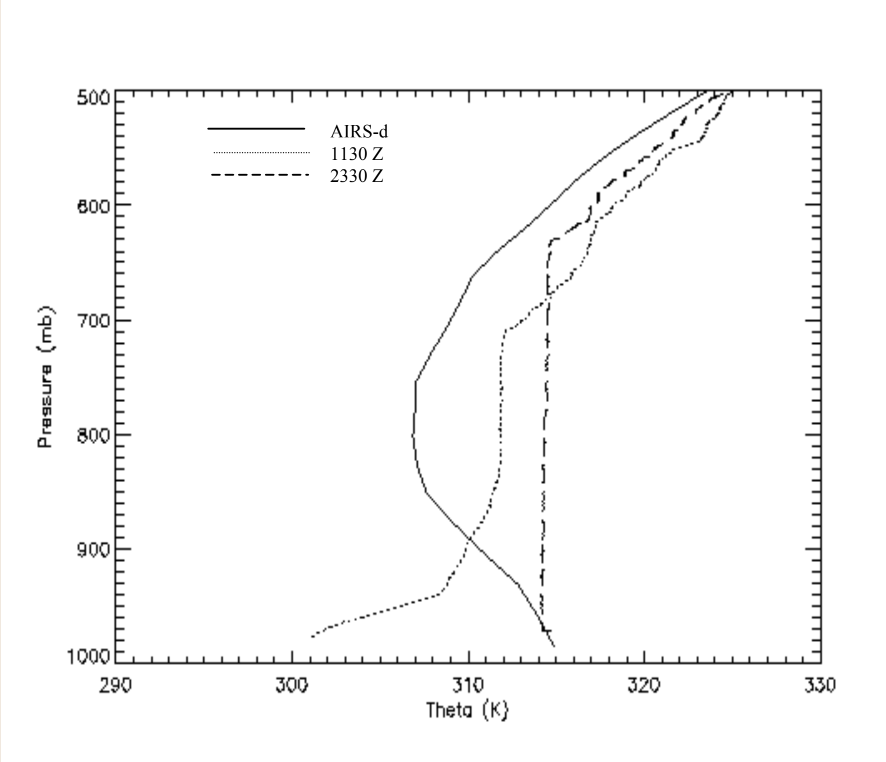
AIRS-Day Evaluation (v3)

Profiles of potential temperature retrieved from AIRS-Day

compared with co-located radiosonde measurements at the ARM-SGP Central Facility



15 June 2003 1930 UTC (1:30pm)



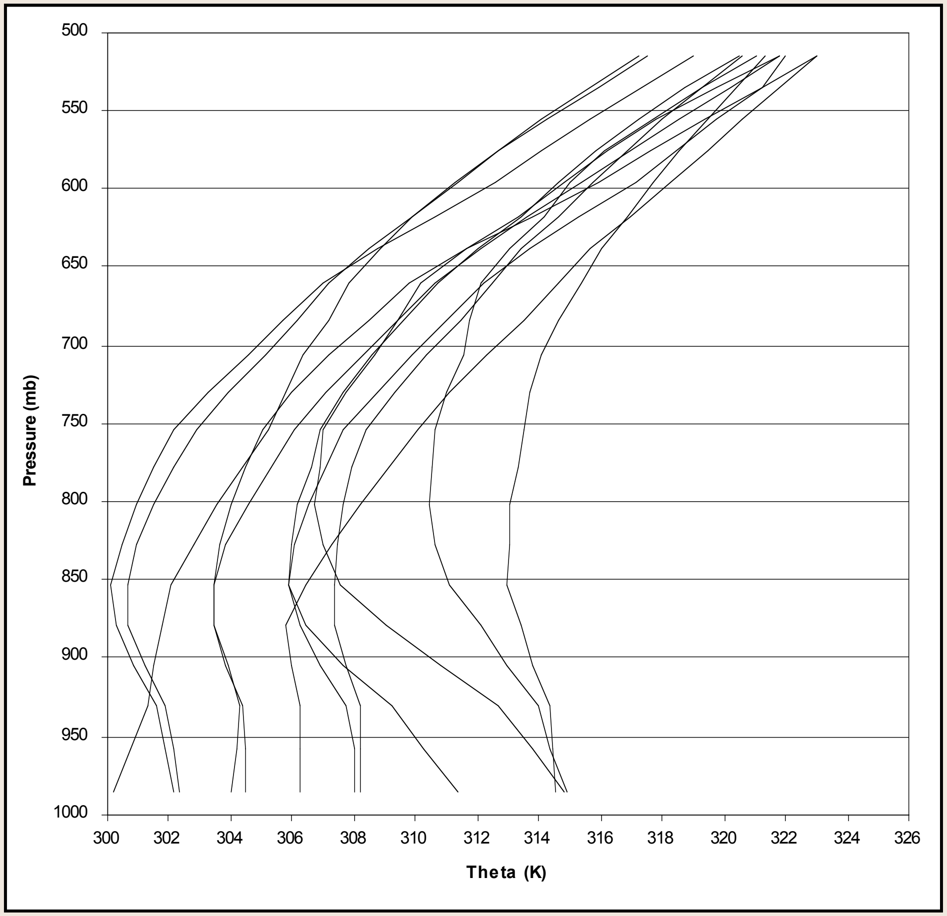
28 July 2003 1930 UTC (1:30pm)

- **AIRS-day responds to surface heating and the magnitude of CBL growth but…..**

  there is a persistent negative bias between 700 and 850 mb

AIRS-Day Variability

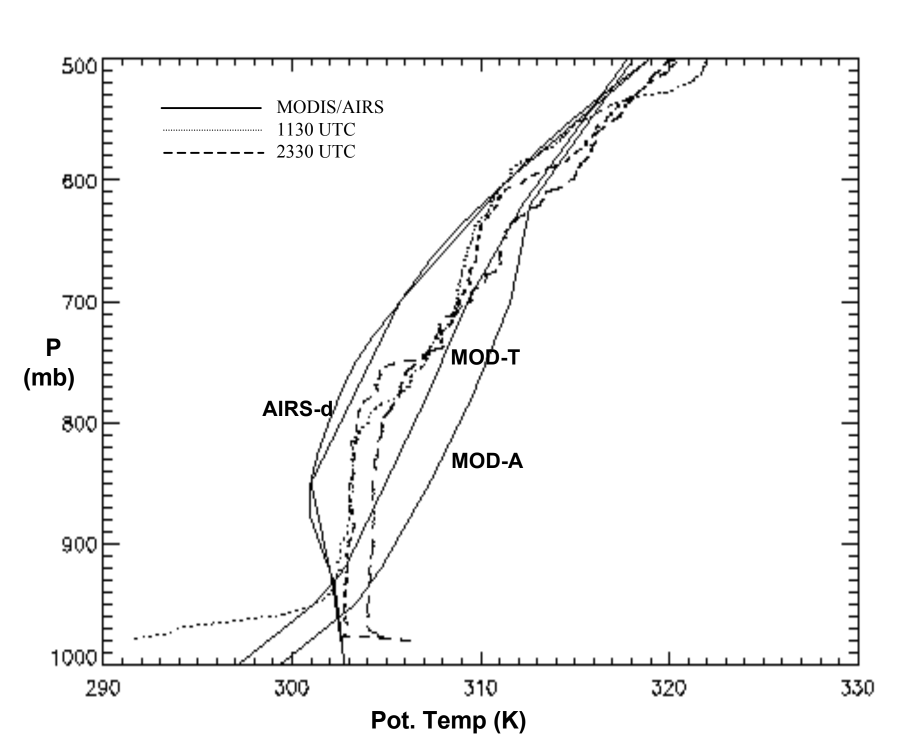
Daytime (1:30 local time) profiles of potential temperature retrieved from AIRS on 12 days in 2003

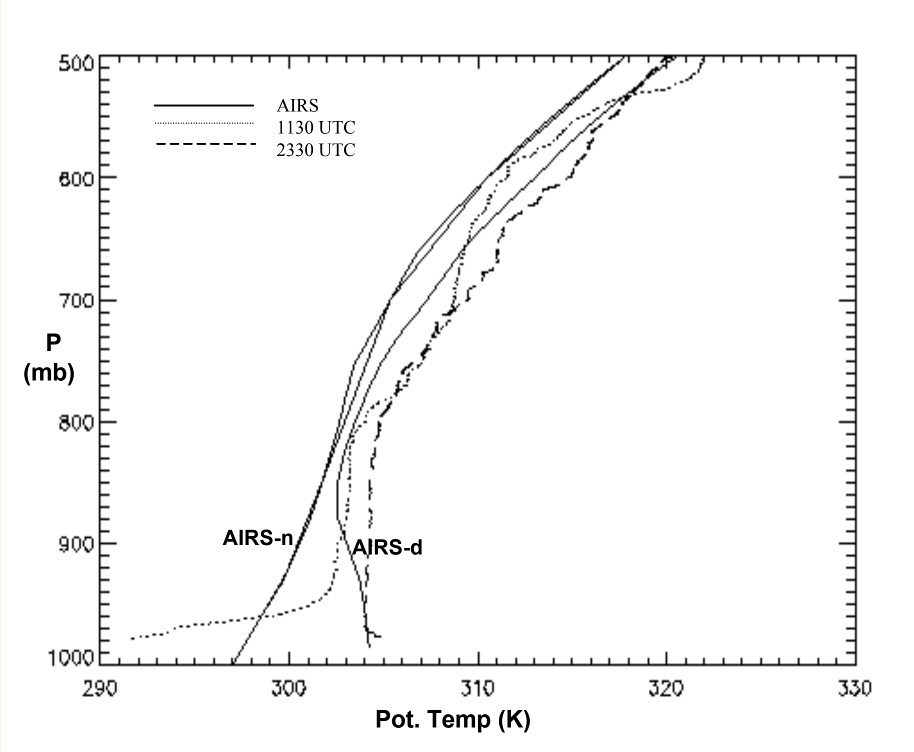


- Bias correction for AIRS-day is not uniform and depends on CBL depth and strength

Diurnal Evaluation of MODIS/AIRS

Profiles of potential temperature retrieved from MODIS and AIRS



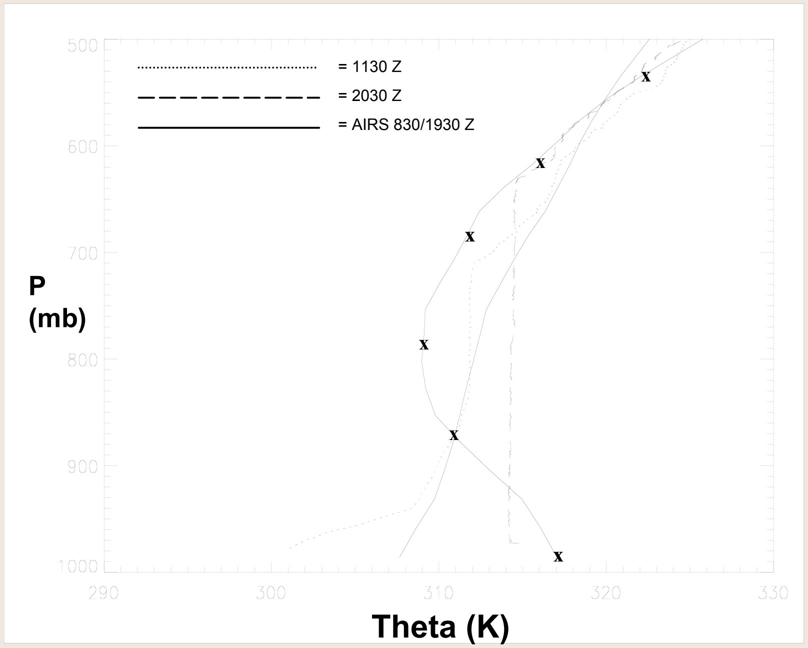


-The signal of CBL heating and evolution is reflected in the difference in AIRS-night and AIRS-day retrievals

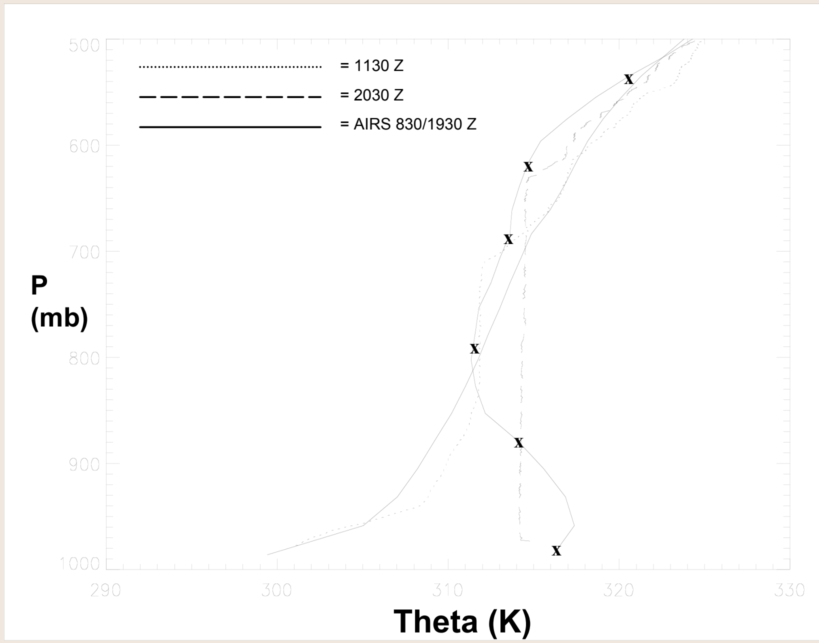
-Specific diagnosis of PBL properties is still lacking…..let's look at **AIRS radiances**

AIRS L2 Retrievals (v3/v5)

Preliminary results for single clear-sky day with very deep residual and mixed-layers



v3

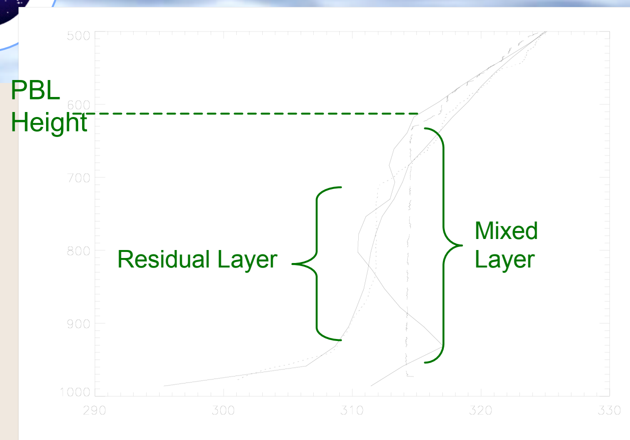


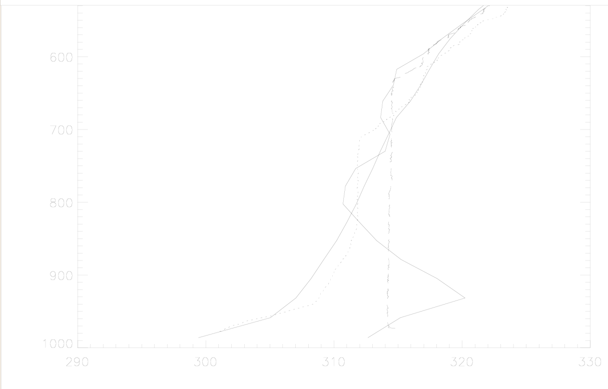
v5

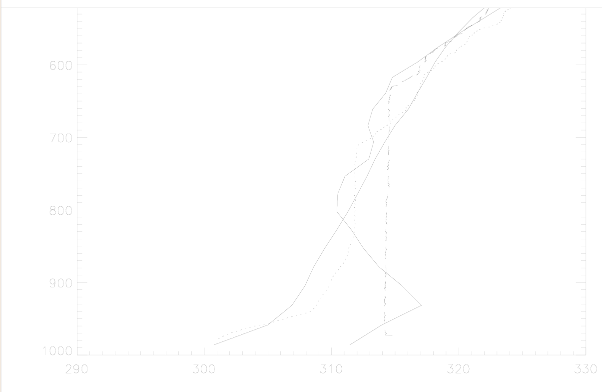
Lamont, OK (ARM-SGP CF)

28 July 2003

AIRS L2 Retrievals (v5)



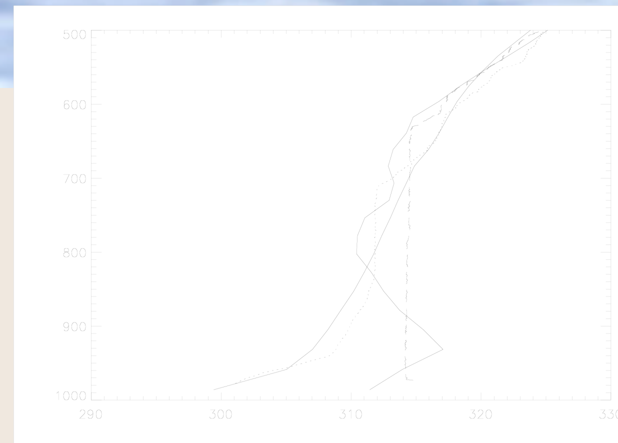


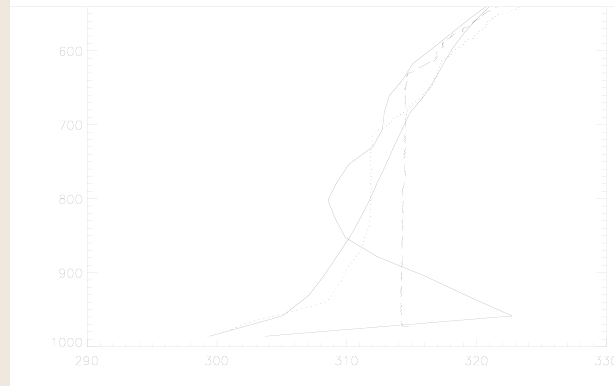


Surrounding Pixels

Lamont, OK (ARM-SGP CF)

28 July 2003





AIRS L2 Retrievals (v5)

Surrounding Pixels

Lamont, OK (ARM-SGP CF)

28 July 2003

Evaluation of AIRS Level 1B Radiances

	h	w	H_s	γ	Storage
7 July	2695	5	182	.004	210
14 June	290	18	80	.02	-52
3 June	1291	23	15	.006	-104

12-hour changes in AIRS radiances (day - night) for three days in 2003

PCA of AIRS Radiances

12-h changes in AIRS Radiances

AIRS-Day Radiances

- **Following Diak et al. (1990's) synthetic studies using HIRS channel specifications to infer surface quantities from radiances**

- **Using full set of 2085 channels, AIRS-day radiances can explain over half the variance in surface soil moisture and heat fluxes over the 44 days period**

AIRS Level 1B Channel Radiances

R^2 values and wavenumbers of ≤ 5 AIRS-Day channel radiances used in linear multiple regressions with CBL and land surface variables

- Radiances in very few channels are correlated surprisingly well with surface moisture, heating, and fluxes due to isolating the 'window' regions
- Additional information on PBL structure can be found when isolating channels that are sensitive to other tropospheric levels

Three channels in the 'window' region + 15 μm CO_2 channels that peak near 2 and 14 mb (tropopause)

Physical Rationale

- Soil drying and surface heating increase radiances from window regions of the spectrum, but this signal obtained by AIRS is weaker than that predicted by Diak et al. (1994).
- A secondary and stronger signal exists near the 15 micron CO2 band, which is *negatively correlated* with surface heating and positively correlated with soil moisture.

Why…………….?

- X Direct surface signal is impossible in these channels
- X Weighting functions peak too high to capture clouds or water vapor effects, confirmed by radiosonde observations.
- ? Seasonal warming and raising of the troposphere from May-Sept results in an actual decrease in ~2-14 mb temperature during the summer.
  - How sensitive is this effect to variability at the surface?
  - Applicable at shorter than-seasonal time scales, and other regions?

Conclusions

- **Results demonstrate *how* the CBL is strongly linked and feeds back upon the land surface.**

- **Initial satellite remote sensing evaluations indicate that:**
  a) signature of the evolution and structure of the CBL (profiles)
  b) the integrated diurnal cycle of surface fluxes (day – night)
  c) information on seasonal soil drying and warming of the troposphere

…..can all be obtained via remote sensing

Future Work:

- Assess the improvement possible in retrieving CBL information using current technology (AIRS) as retrievals improve (e.g. v5)
- Analysis of AIRS moisture retrievals in the PBL over land
- Investigate AIRS level 1B channel correlations for other locations and surface/seasonal conditions

Outline

The Role of the CBL in L-A Interactions

L-A Coupling Diagnostics

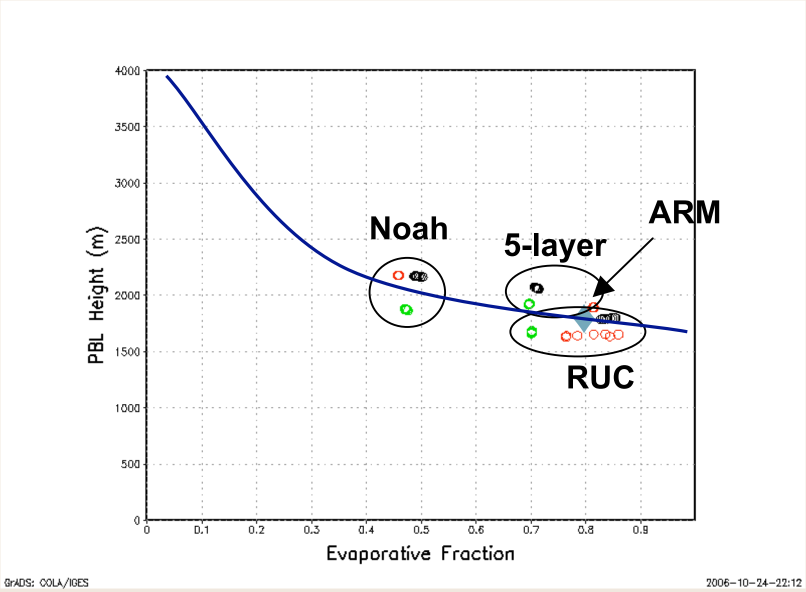
Remote sensing of CBL properties

Incorporating CBL Observations into ‘LoCo’

What is LoCo?

Overarching goal:

- ***To accurately understand, model and predict the role of Local Coupling of land – atmosphere interactions in the evolution of land-atmosphere and PBL fluxes and state variables.***



→ **CBL information obtained via remote sensing can be used to diagnose the degree of L-A coupling and help diagnose and improve land surface and atmospheric models**

Thank You !

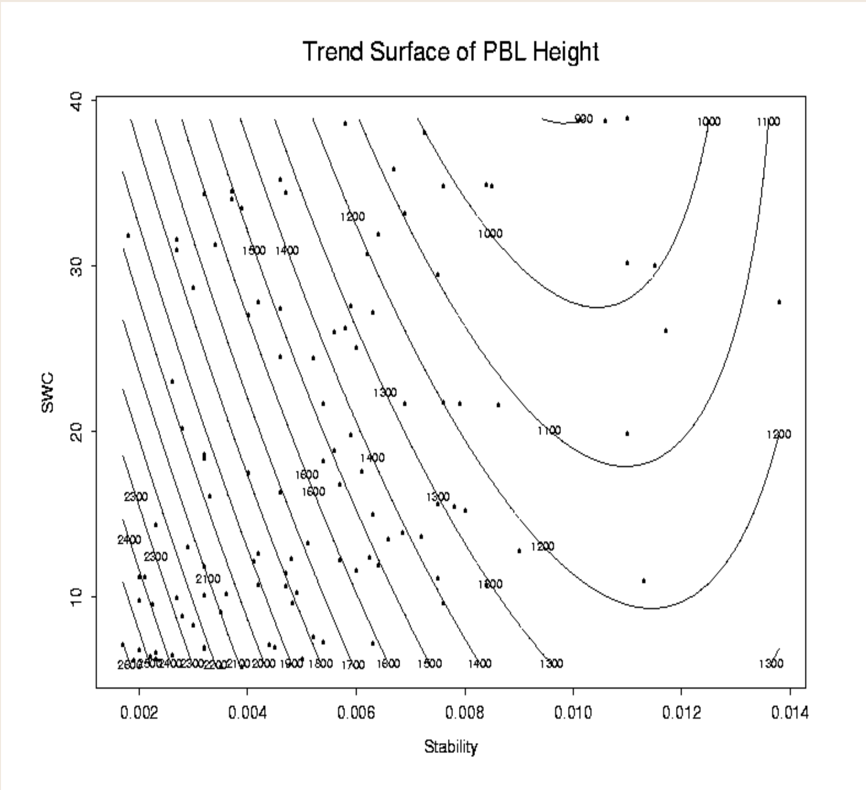
NASA Earth System Science Fellowship

NASA Energy and Water Cycle Study (NEWS)

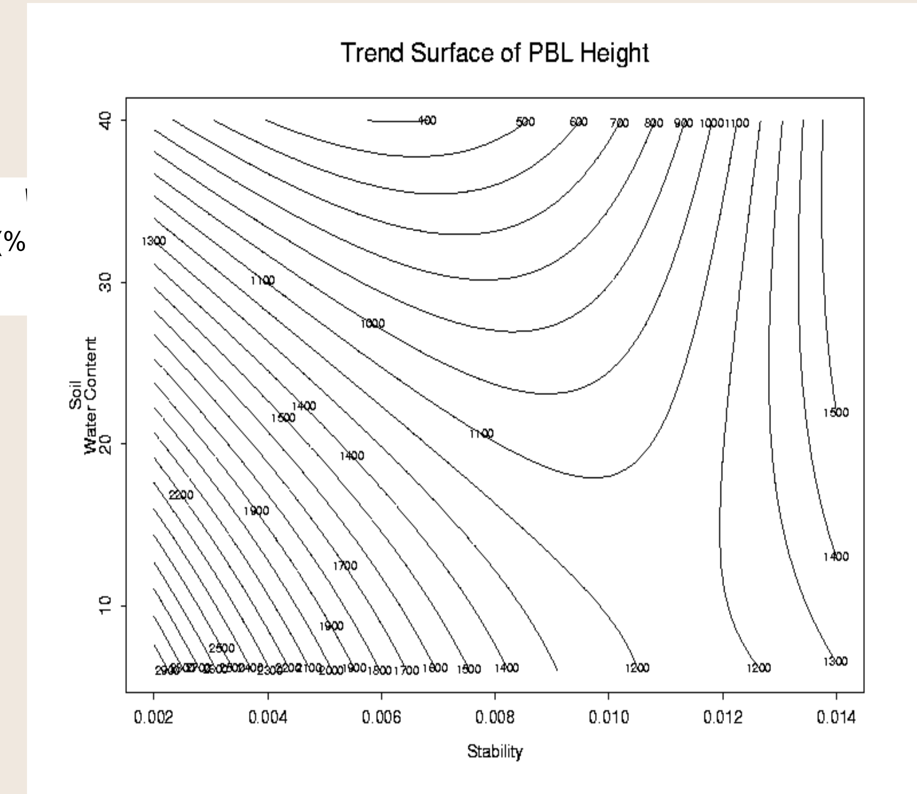
Observed and Modeled CBL Diagnostics

A coupled SCM (OSU; Mahrt and Pan 1984) can be used to simulate these relationships

→ 100 simulations covering full range of observed soil moisture and stability



ARM-SGP (previous slide)

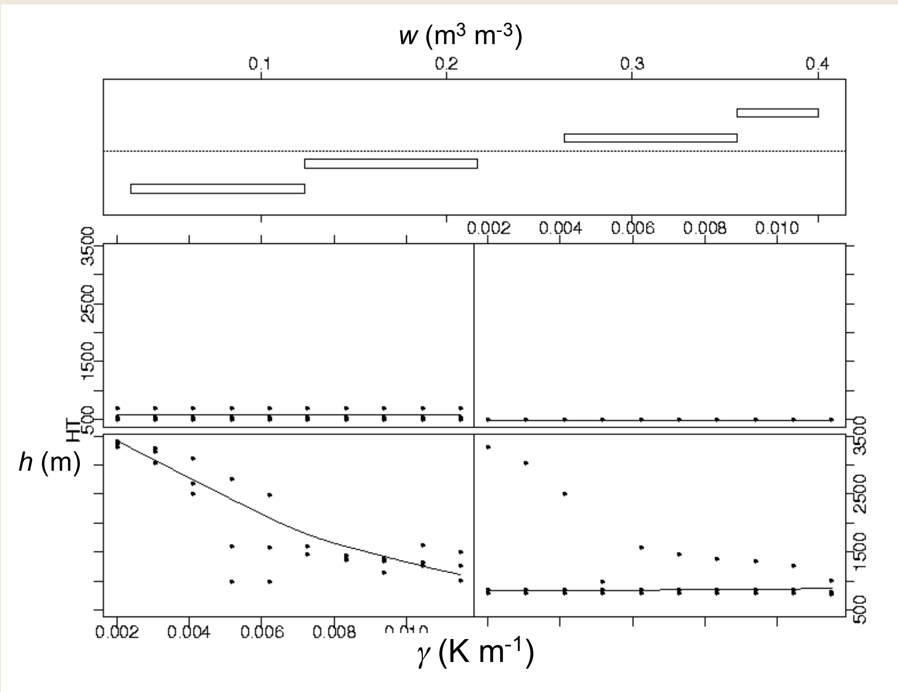


OSU Simulations

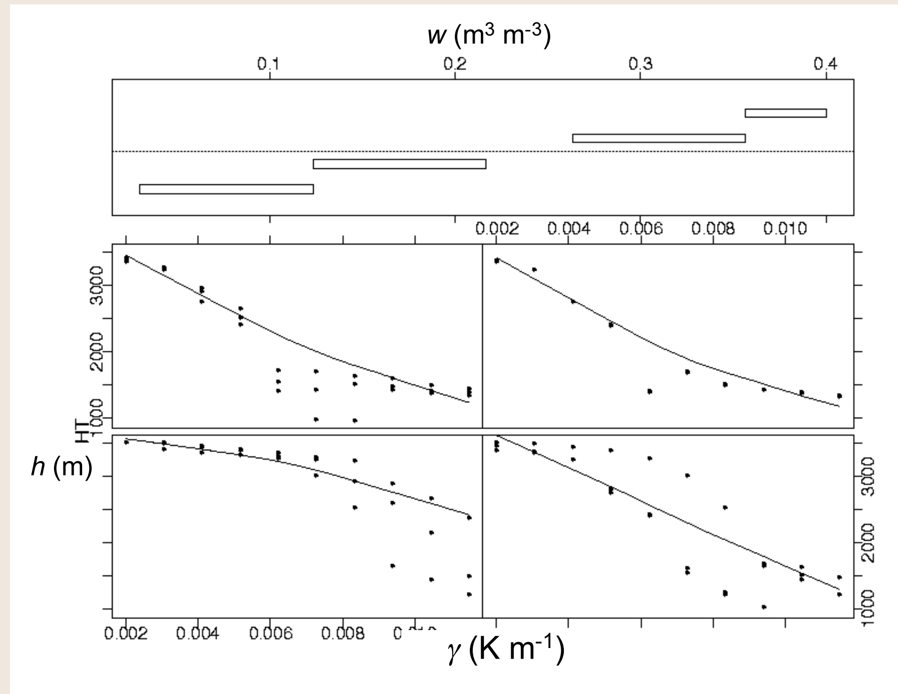
Predictions of CBL Height from OSU simulations agree well with observed (R^2 = 0.83)

Simulated CBL Diagnostics

How does vegetation cover affect the principle controls on PBL height?



Leaf Area Index = 0.5



Leaf Area Index = 6.0

We can identify similar relationships for soils….

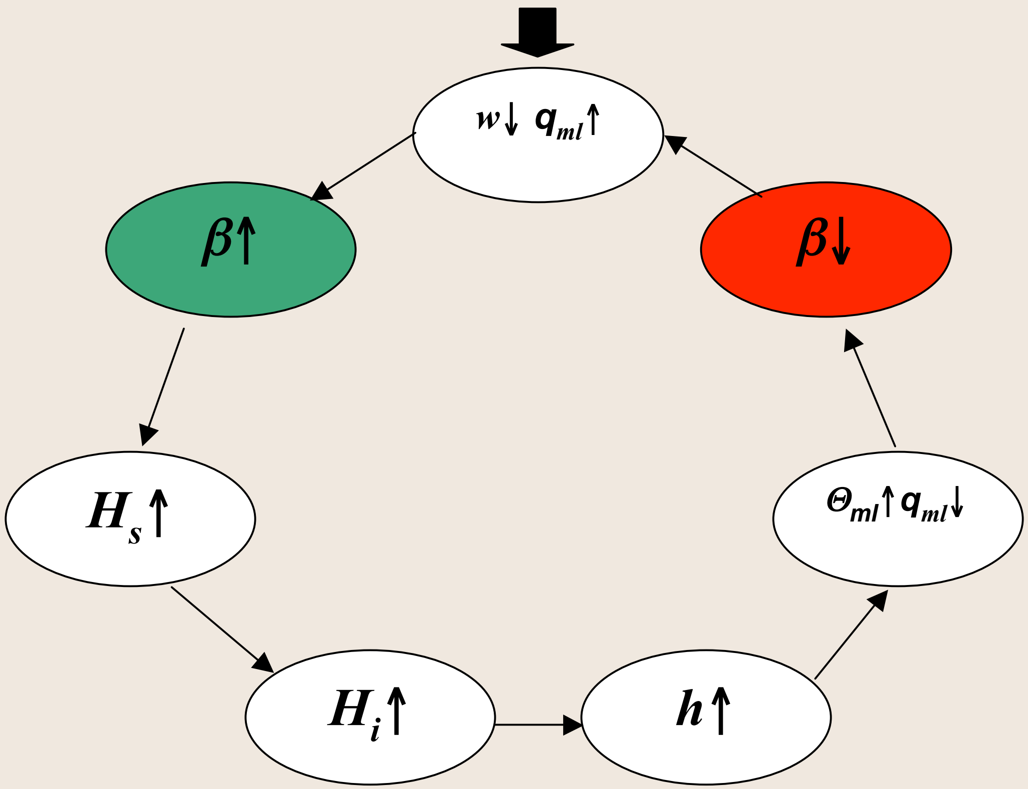
Impact of Vegetation Stress

OSU simulations of soil moisture-flux relationships with varying LAI

- For high vegetation cover, water can be transported from deeper soil layers and evaporation remains ***atmosphere-limited***.
- Evaporation becomes ***soil-limited*** more quickly for bare soils.

Atmosphere-Limited Feedback

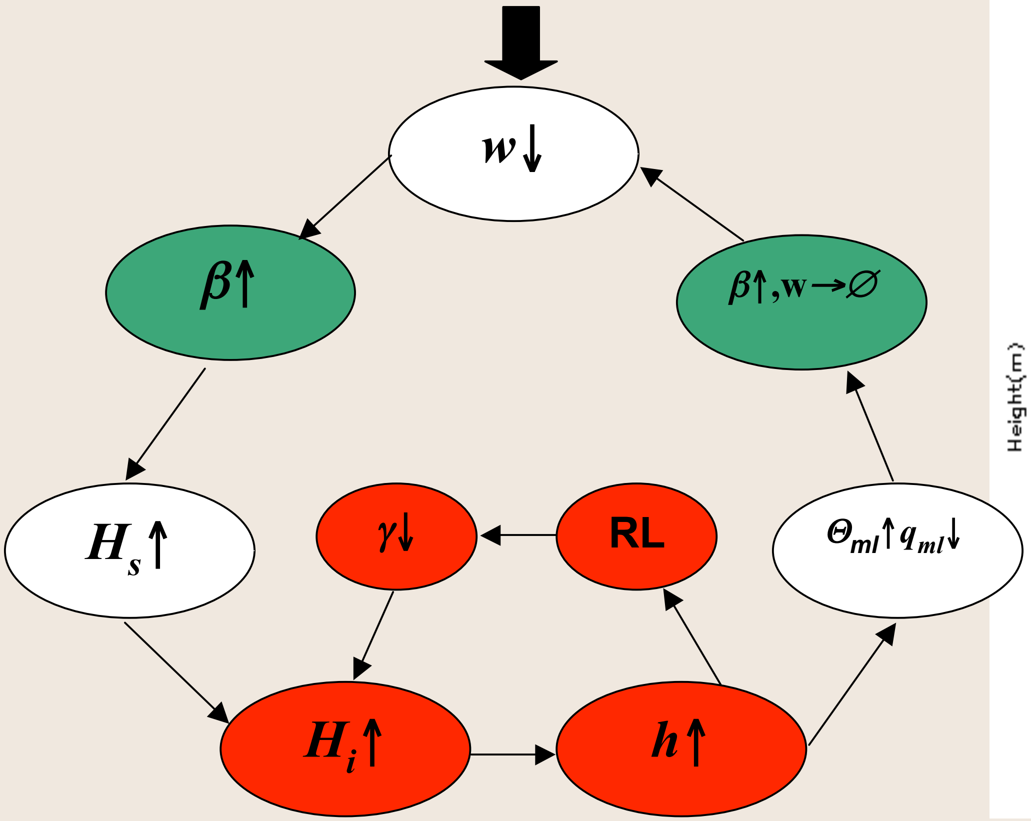
Saturated Soil Begins Evaporating

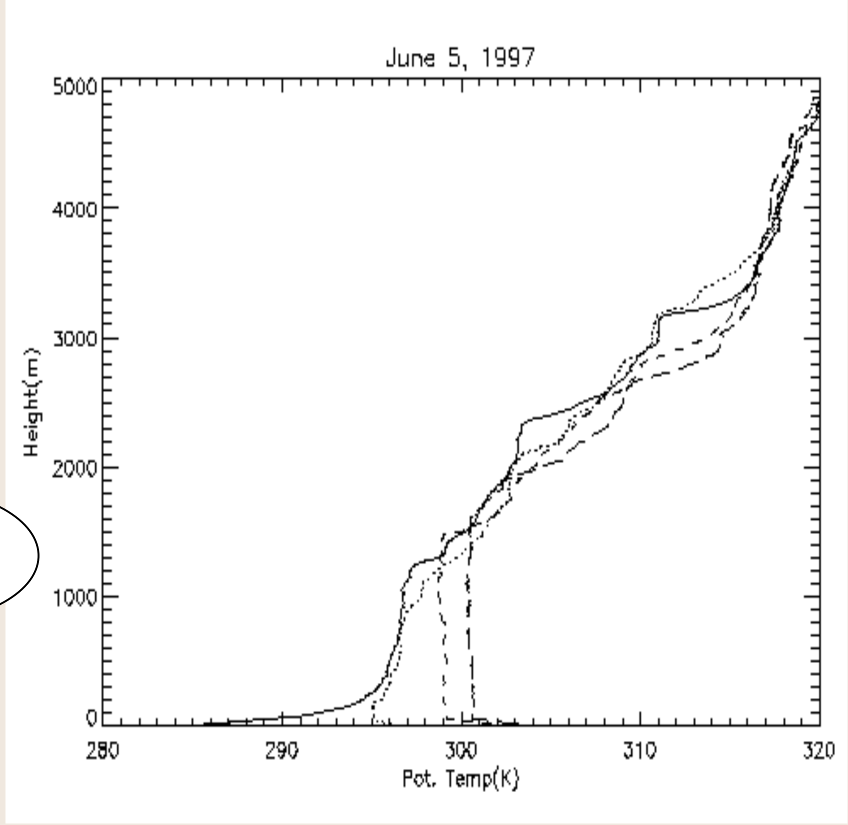


CBL growth maintains evaporative rate…..

Soil-Limited Feedback

Soil Water Decreases Below Dry Threshold





Dry soils promote the existence and persistence of a residual layer that acts to enhance CBL growth and soil desiccation

Feedbacks: Fluxes vs. Soil Moisture

The main influence of CBL coupling is seen through changes in the atmospheric demand for ET….

A) For moist soils, a *negative* feedback on ET occurs due to CBL coupling.

Feedbacks: Fluxes vs. Soil Moisture

B) For dry soils, a *positive* feedback on ET and drought occurs…

Are offline LSM's and data assimilation affected…?

Importance of the Residual Layer

CBL height versus residual layer depth

- Existence of a residual layer supports significant CBL growth on the following day
- There is predictive ability and information in the structure of the CBL that determines flux equilibrium at the land surface

	n	w	γ	h	Min H_s	Max H_s
Days with RL	31	0.13	0.0035	2177	36.8	242.1
Days without RL	101	0.20	0.0065	1424	33.9	243.8

Santanello, J. A., M. A. Friedl, and M. B. Ek: Convective Planetary Boundary Layer Interactions with the Land Surface at Diurnal Time Scales: Diagnostics and Feedbacks. *J. Hydrometeorol.*, under review.

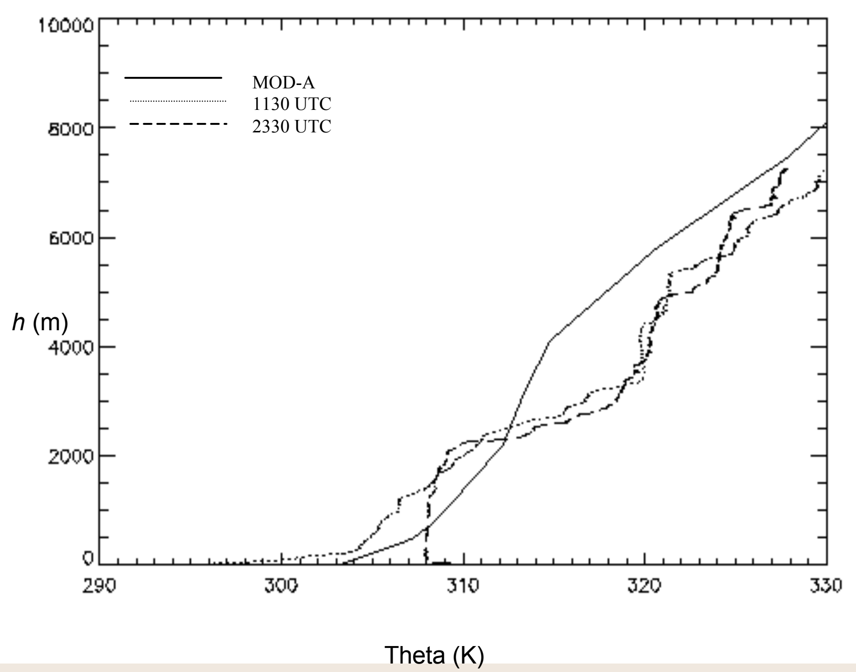
Synthetic MODIS/AIRS Profile Retrievals

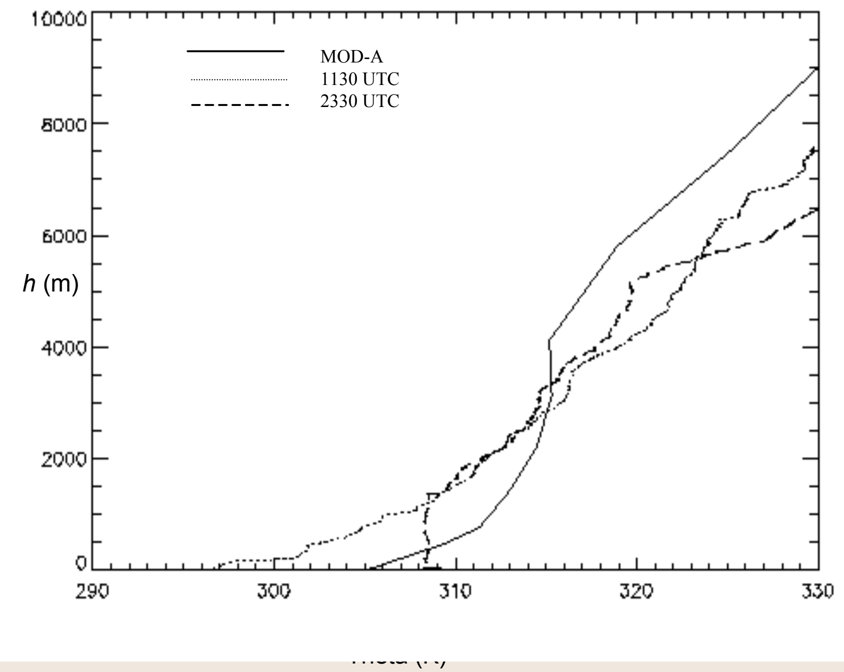
Generated from nearest vertical levels of radiosonde observations to specific standard retrieval levels of each sensor (23 June 2001)

MODIS-Aqua Evaluation

Profiles of potential temperature retrieved from MODIS-Aqua

compared with co-located radiosonde measurements at the ARM-SGP Central Facility





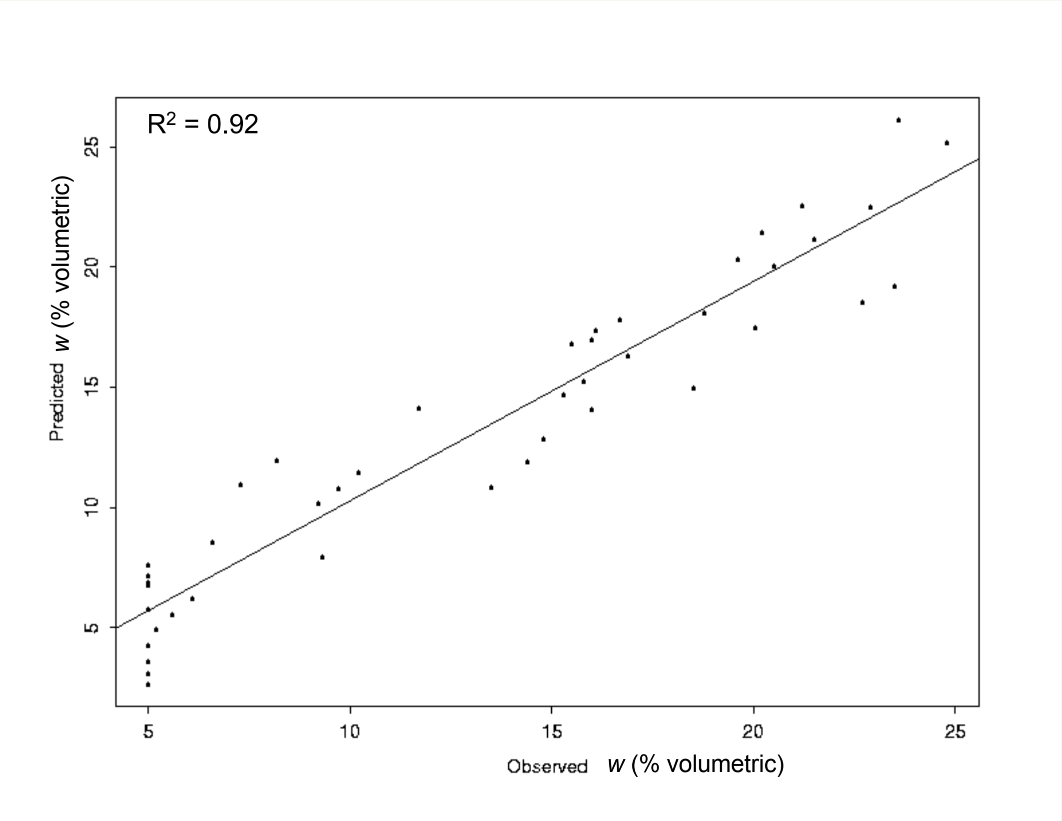
5 July 2003 1930 UTC (1:30pm)

10 July 2003 1945 UTC (1:45pm)

- MODIS-Aqua responds to the heating of the mixed-layer (bend point ~4 km)
- Spectral resolution is not sharp enough to capture mixed-layer structure of CBL height

AIRS Radiances

Observed soil moisture versus that predicted by the AIRS-d 5 channel multiple regression.



Three channels in the 'window' region + 15 μm CO_2 channels that peak near **2 and 14 mb**

NASA Funding for LoCo Development

NASA model and observation products for the study of land-atmosphere coupling and its impact on water and energy cycles

C. D. Peters-Lidard, W-K. Tao, M. Bosilovich, M. Rodell, and W. Lau (NASA/GSFC),
J. Santanello (UMDCP/ESSIC), J. Chern (UMBC/GEST)

- **Objectives (2005-2010):**
  - Study factors controlling Land-Atmosphere Coupling (LAC) and the effect of this coupling on efforts to assimilate NASA observations into water and energy cycle prediction systems.
  - Develop a suite of modeling and observational products to study the strength of local LAC, and provide these products to the developing GLASS “Local Coupled Action” (LoCo) project community and the NEWS science team.

- **Community Deliverables (2007):**
  - Boundary and initial conditions for LoCo sites extracted from the Goddard fvGCM/MMF, used to drive a Single Column Model (SCM) coupled to a suite of land surface models.
  - Source code for the coupled Land Information System (LIS), with the combined Weather Research and Forecasting Model (WRF)/Goddard Cumulus Ensemble (GCE) models.
  - Data assimilation modules, which have been under development at NASA by Houser, Zhan, Reichle et al. (soil moisture), Rodell et al. (snow), Bosilovich et al. (skin temperature).

Assimilation Activities in LoCo

- Land Surface assimilation
  - MODIS Snow Cover (M. Rodell and P. Houser), SWE
  - AMSR-E/TMI/Hydros Soil Moisture (R. Reichle and R. Koster)
  - Skin Temperature (M. Bosilovich)
- Screen-level assimilation
  - Incorporate relationships shown here (2m-temp change)
  - Examine relationship to profile data and assimilation
- PBL profile and radiance data
  - AIRS (day + night overpasses)
  - Bias in PBL temp, merged water vapor – (E. Fetzer; AIRS team)
  - Profiles will only improve going forward

Empirical Approaches

Estimating CBL properties from AIRS profiles

- **CBL Height**
  - Vertical change in θ from the lowest (2m) level to the inflection point (700-850 mb) of the AIRS-d profiles.
    - Correlates to observed ***h*** ($R^2 = 0.90$)

- **Change in 2m-Potential Temperature**
  - Initial θ can be estimated by extrapolating the slope of free-atmosphere temperature retrieval to the surface.
  - Final θ estimated from lowest level AIRS-d estimate
    - Correlates with observed $\Delta\theta_{2m}$ ($R^2 = 0.72$).

- **Stability**
  - AIRS-n profiles correlate with observed γ ($R^2 = 0.61$).

NASA's Land Information System

Uncoupled

LIS

Coupled

Station Data

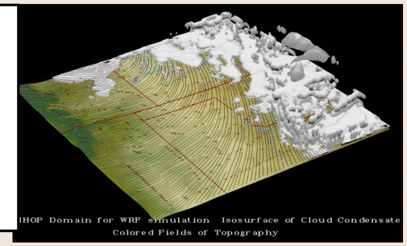
Global, Regional (Re-)Analyses or Forecasts

Satellite Products

LSM Ensemble
Noah, CLM2, Mosaic, HYSSiB, VIC

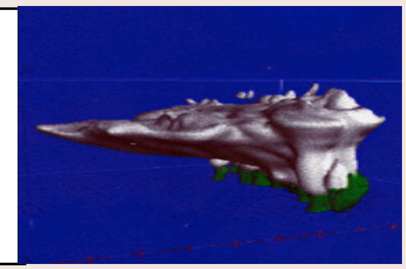
ESMF

WRF



ESMF

GCE

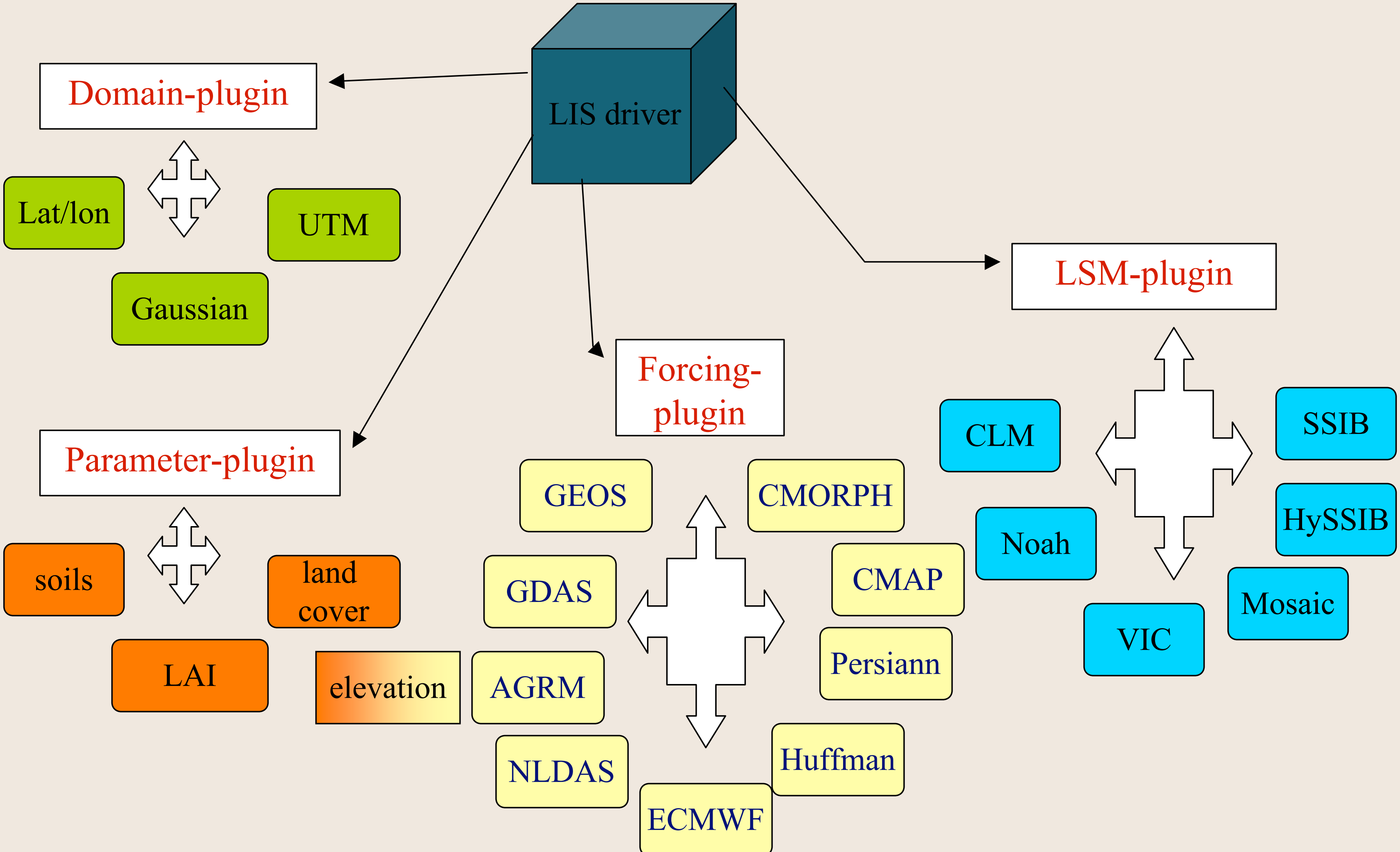


GrADS/DODS Server

Code and Documentation at
http://lis.gsfc.nasa.gov

Kumar et al., 2005, EMS, in press

LIS "Plugin" Design



Empirical Approaches

MODIS Brightness Temperatures

- Weighting functions for bands 27, 28, and 30-36 peak at different vertical levels.
- Differences between brightness temperatures at the surface (31,32) and these levels are related to CBL structure.
- PBL height is correlated to changes in band differentials